An Experimental Overview of the X, Y & Z Charmoniumlike Mesons

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A review of some of the recent experimental developments concerning the X, Y and Z charmoniumlike mesons states is presented.

Introduction

The X, Y & Z particles are an assortment of meson-resonance-like peaks that were discovered by the BaBar and Belle B-factory experiments. A common feature is that they are seen to decay to final states that contain charmed (c) and anticharmed ($\bar{c}$) quarks and, thus, almost certainly contain a $c\bar{c}$ quark pair among their constituent particles. The spectrum of conventional mesons that are comprised of only a $c\bar{c}$ quark pair, *i.e.* the "charmonium mesons," is generally considered to be the most well understood hadronic system, both experimentally and theoretically, and most of the XYZ candidate states do not match well to any of the remaining unassigned charmonium levels. As a result, at least some of these states have been touted as candidates for "exotic" mesons, *i.e.* mesons with a more complex substructure than the simple quark-antiquark anzatz of the venerable Quark-Parton-Model (QPM).

In particular, if the Z states, seen by Belle as peaks in the $\pi^+\psi'$ and $\pi^+\chi_{c1}$ invariant mass distributions [1] in $B \to K\pi^+\psi'$ [2] and $B \to K\pi^+\chi_{c1}$ [3], respectively, are mesons, they would necessarily have a minimal quark substructure of $c\bar{c}u\bar{d}$ and be, therefore, manifestly exotic. Here the experimental situation remains a bit uncertain in that an analysis by the BaBar group does not confirm (or contradict) Belle's claim for the $Z(4430)^+ \to \pi^+\psi'$ mass peak [4]. The situation concerning the charged Z states are discussed at this meeting by Ruslan Chistov (Belle), Claudia Patrigiani (BaBar) and in a panel discussion chaired by Ryan Mitchell. I provide some of my own comments on the Z states below.

Other topics covered here include: new results from Belle and CDF on the mass of the $X(3872)$; a comment on the J^{PC} determination of the $X(3872)$; some discussion on the X and Y states with masses near 3940 MeV including the first public presentation of a new Belle study of the process $\gamma\gamma \to \omega J/\psi$, which is dominated by a narrow peak near 3915 MeV.

The states with mass near 3940 MeV

In 2005, Belle reported observations of three states with masses near 3940 MeV: the $X(3940)$, seen as a $D^*\bar{D}$ mass peak in exclusive $e^+e^- \to J/\psi D^*\bar{D}$ annihilations [5]; the $Y(3940)$, seen as a near-threshold $\omega J/\psi$ mass peak in the decay $B \to K\omega J/\psi$ [6]; and the $Z(3930)$, seen as a $D\bar{D}$ mass peak in untagged $\gamma\gamma \to D\bar{D}$ events [7]. Of these, only the $Z(3930)$ has been convincingly assigned to a previously unfilled charmonium level.

The $Z(3930)$ production angle distribution matches well the $\sin^4\theta^*$ behavior expected for a $J=2$ meson and its mass ($3929 \pm 5 \pm 2$ MeV), width ($29 \pm 10 \pm 2$ MeV) & $\gamma\gamma$ production rate match well to expectations for the 2^3P_2 $c\bar{c}$ charmonium state, which is commonly called the χ'_{c2}. There is general agreement that the $Z(3930)$ is, in fact, the χ'_{c2}.

The $X(3940)$ is produced in association with a J/ψ in the $e^+e^- \to J/\psi X(3940)$ annihilation process, which unambiguously fixes its C-parity as $C = +1$. Furthermore, the only known charmonium states that are seen to be produced via the process $e^+e^- \to J/\psi(c\bar{c})$ have $J=0$, which provides some circumstantial evidence that the $X(3940)$ has $J=0$. This, taken together with the fact that the $X(3940)$ was discovered via its $D^*\bar{D}$ decay channel and is not seen to decay to $D\bar{D}$ – a decay channel that is preferred for 0^{++} and forbidden for 0^{-+} – indicates that $J^{PC} = 0^{-+}$ is its most likely quantum number assignment. The unfilled 0^{-+} state with the closest expected mass value is the 3^1S_0 η''_c, which potential model predictions put at 4043 MeV (or higher) [8], well above the $X(3940)$'s measured mass: $3942 \pm 2 \pm 6$ MeV [9].

The $Y(3940)$ mass is well above open-charm mass thresholds for decays to $D\bar{D}$ or $D^*\bar{D}$ finally states, but was discovered via its decay to the hidden charm $\omega J/\psi$ final state. This implies an $\omega J/\psi$ partial width that is much larger than expectations for charmonium.

Are $X(3940)$ and $Y(3940)$ the same state?

In a recently reported study of $B \to KD^*\bar{D}$ decays, Belle searched for, and did not find, a signal for $B \to KY(3940)$; $Y(3940) \to D^*\bar{D}$ [10]. The quoted upper limit on this mode corresponds to a lower limit on the branching fraction ratio:

$$\frac{\mathcal{B}(Y(3940) \to \omega J/\psi)}{\mathcal{B}(Y(3940) \to D^{*0}\bar{D}^0)} > 0.75 \qquad (1)$$

at the 90% confidence level. Likewise, Belle searched for evidence for $X(3940) \to \omega J/\psi$ by searching for $\omega J/\psi$ systems recoiling from a J/ψ in $e^+e^- \to \omega 2J/\psi$ annihilations [5]. Here no signal is seen and an upper limit

$$\frac{\mathcal{B}(X(3940) \to \omega J/\psi)}{\mathcal{B}(X(3940) \to D^{*0}\bar{D}^0)} < 0.60 \qquad (2)$$

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was established at the 90% CL. These limits would be contradictory if the $X(3940)$ and the $Y(3940)$ were the same state seen in different production modes. Thus, the best current evidence indicates that these two states are distinct.

BaBar's confirmation of the $Y(3940)$

In 2008, BaBar [11] reported a study of $B \to K\omega J/\psi$ in which the $\omega J/\psi$ invariant mass distribution shows a near-threshold peaking that is qualitatively similar to $Y(3940)$ peak previously reported by Belle. However, the BaBar values for mass and width derived from fitting their data are both lower than the corresponding values reported by Belle: $M = 3914^{+3.8}_{-3.4} \pm 1.6$ MeV (BaBar) compared to $3943 \pm 11 \pm 13$ MeV (Belle), and $\Gamma = 33^{+12}_{-8} \pm 0.6$ MeV (BaBar) compared to $87 \pm 22 \pm 26$ MeV (Belle). Part of the difference might be attributable to the larger data sample used by BaBar (350 fb^{-1} compared to Belle's 253 fb^{-1}), which enabled them to use smaller $\omega J/\psi$ mass bins in their analysis.

Belle's new $\omega J/\psi$ mass peak in $\gamma\gamma \to \omega J/\psi$

New to this meeting is a report from Belle of a dramatic and rather narrow peak in the cross section for $\gamma\gamma \to \omega J/\psi$ [12] that is consistent with the mass and width reported for the $Y(3940)$ by the BaBar group.

Belle selects events with $\pi^+\pi^-\pi^0$ and $\ell^+\ell^-$ ($\ell = \mu$ or e) tracks that have a net transverse momentum that less than 100 MeV. In events with $M_{\ell^+\ell^-}$ near $m_{J/\psi}$, the three pion system is found to be dominated by $\omega \to \pi^+\pi^-\pi^0$ decays; likewise, in events where $M_{3\pi}$ is near m_ω, the dileptons are almost all from $J/\psi \to \ell^+\ell^-$ decays. After application of the requirements $|M_{3\pi} - m_\omega| < 30$ MeV & $|M_{\ell^+\ell^-} - m_{J/\psi}| < 25$ MeV and vetoing events with a $\psi' \to \pi^+\pi^- J/\psi$, the invariant mass distribution for the ω J/ψ candidates, shown in Fig. 1, shows a sharp peak near threshold and not much else.

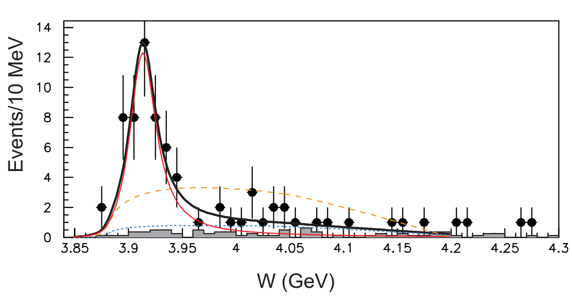

Figure 1: The $\omega J/\psi$ mass distribution for selected events.

The solid curve in Fig. 1 shows the result of a fit that uses a phase-space-weighted, resolution-broadened S-wave Breit Wigner (BW) function plus a smooth background function that is forced to zero for masses below threshold. The fit, which has a $\chi^2/ndf = 33.1/29$, gives *preliminary* results for the resonance parameters of this peak, dubbed the $X(3915)$, of:

$$
\begin{aligned}
M &= 3914 \pm 4 \pm 2 \text{ MeV}; && (3)\\
\Gamma &= 28 \pm 12^{+2}_{-8} \text{ MeV}; && (4)\\
N_{evts} &= 60 \pm 13^{+3}_{-14}. && (5)
\end{aligned}
$$

The dashed curve in Fig. 1 shows the result of a fit with no BW term. The statistical significance of the signal, determined from the square root of the change in likelihood for the fits with and without a BW term and with the change in ndf taken into account, is 7.1σ. The systematic errors on these parameters are determined by varying the selection requirements and fitting procedure.

This preliminary value for the mass is about 2σ different from that of the $Z(3930)$ ($M = 3929 \pm 5 \pm 2$ MeV, indicating that these two peaks are distinct and not different decay channels of the same state. On the other hand, there is good agreement between these preliminary results and the mass and width quoted by BaBar for the "$Y(3940)$," which is also seen in $\omega J/\psi$.

The $\omega J/\psi$ acceptance depends on the J^P value. For $J^P = 0^+$, Belle determines

$$\Gamma_{\gamma\gamma}(X(3915))\mathcal{B}(X(3915) \to \omega J/\psi) = 69 \pm 16^{+7}_{-18}\text{eV}, \quad (6)$$

where $X(3915)$ is used to denote this new candidate state.

Whether or not the $X(3915)$ is the same as the $Y(3940)$, it has the same difficulty with a charmonium assignment. Using the total width measurement given above, Eq. 6 can be rewritten as: $\Gamma_{\gamma\gamma}(X(3915))\Gamma(X(3915) \to \omega J/\psi) \simeq 2000$ keV^2, (albeit with large ($\sim \pm 50\%$) errors). If for $\Gamma_{\gamma\gamma}$ we apply a value that is typical for charmonium, i.e. $1 \sim 2$ keV), we find a partial $\Gamma(X(3915) \to \omega J/\psi) \sim \mathcal{O}$(1 MeV), which is quite large for charmonium. Here a $J^P = 2^+$ assignment would help some, but not too much.

The $X(3872)$

The $X(3872)$ was discovered by Belle in 2003 [13] as a narrow peak in the $\pi^+\pi^- J/\psi$ invariant mass distribution from $B^+ \to K^+\pi^+\pi^- J/\psi$ decays. This peak was subsequently confirmed by CDF [14], D0 [15] and BaBar [16]. CDF and D0 see $X(3872)$ produced promptly in inclusive $p\bar{p}$ collisions as well as in B meson decays. In all of the experiments, the invariant mass distribution of the dipion system is consistent with originating from $\rho \to \pi^+\pi^-$ [17]. If this is the case, the C-parity of the $X(3872)$ must be $C = +1$. Charmonium states are all Isosinglets; the decay charmonium$\to$ $\rho J/\psi$ violates Isospin and should be strongly suppressed.

Comment on the J^{PC} value of the $X(3872)$

A study of angular correlations among the $\pi^+\pi^- J/\psi$ final state particles by CDF led them to conclude that the only likely J^{PC} assignments for the $X(3872)$ are 1^{++} and 2^{-+}, with 1^{++} preferred [18]. Subsequently, the 2^{-+} assignment has been further disfavored by BaBar's report

of $> 3\sigma$ significance signals for $X(3872)$ decays to both $\gamma J/\psi$ and $\gamma\psi'$ [19]. The radiative transition of a 2^{-+} state to the J/ψ or ψ' would have to proceed via a higher order multipole term and be highly suppressed. For these reasons, the most likely J^{PC} is 1^{++}.

The $X(3872)$ *mass*

An intriguing feature of the $X(3872)$ is its close proximity in mass to the $D^{*0}\bar{D}^0$ mass threshold. This has stimulated a number of papers that interpret the $X(3872)$ as a molecule-like arrangement comprised of a D^{*0}- and $\bar{D}^0$-meson [20]. Critical to these models is whether the $X(3872)$ mass is above or below $m_{D^{*0}} + m_{D^0}$. In 2008, Belle reported a new result for the mass of the $X(3872)$ determined using the $X(3872) \to \pi^+\pi^- J/\psi$ decay mode: $M^{Belle}_{X(3872)} = 3871.46 \pm 0.37 \pm 0.07$ MeV [21]. This year, the CDF group reported an even more precise measurement of the mass using the same decay channel: $M^{CDF}_{X(3872)} = 3871.61 \pm 0.16 \pm 0.19$ MeV [22]. A new world average that includes these new measurements plus other results that use the $\pi^+\pi^- J/\psi$ decay mode is $M^{avg}_{X(3872)} = 3871.46 \pm 0.19$ MeV. This puts the $X(3872)$ within about one part in 10^4 of the $D^{*0}\bar{D}^0$ mass threshold: $m_{D^{*0}} + m_{D^0} = 3871.81 \pm 0.36$ MeV [23], and sets the binding energy of any possible $D^{*0}\bar{D}^0$ component of the $X(3872)$ at -0.35 ± 0.41 MeV. Note that any significant improvements in the precision of this quantity will require improvement in the D^0 mass determination, which is currently known to within ± 180 keV [23]. This is something that BES-III could provide.

Are there $X(3872)$ *partner states?*

Another interpretation suggests that the $X(3872)$ is a tightly bound diquark-diantiquark system [24, 25]. In this picture the existence of nearby partner states is expected. The observed $X(3872)$, which is produced in B^+ decays, is interpreted as a $cu\bar{c}\bar{u}$ combination (dubbed X_L). In $B^0 \to K_S\pi^+\pi^- J/\psi$, one should see a partner state, the $X_h = cd\bar{c}\bar{d}$ combination,which differs in mass by 8 ± 3 MeV [26]. In addition, Isospin and Flavor-$SU(3)$ partner states (*e.g.,* $X^+ = cu\bar{c}\bar{d}$ and $X_s = cs\bar{c}\bar{d}$) are also expected to exist.

BaBar searched for a charged version of the $X(3872)$ in the $\pi^-\pi^0 J/\psi$ mass distribution in $B \to K\pi^-\pi^0 J/\psi$ decays and found no evidence for a signal in either B^0 or B^+ decays [27]. The BaBar 90% CL upper limit on the number of $B^0 \to K^+X^-$ events is 15.9 events, which should be compared to the Isospin symmetry expectation of 75 ± 25. They rule out an isovector hypothesis for the $X(3872)$ with 99.99% confidence.

Both Belle [21] and BaBar [28] measured the $X(3872)$ mass for $B^+ \to K^+\pi^+\pi^- J/\psi$ and $B^0 \to K_s\pi^+\pi^- J/\psi$ decays separately. They both find mass differences that are consistent with zero: $M_{X_H} - M_{X_L} = 0.2 \pm 0.9 \pm 0.3$ MeV for Belle and $2.7 \pm 1.6 \pm 0.4$ MeV for BaBar. The CDF group tried fitting their ~6000 event $X(3872) \to \pi^+\pi^- J/\psi$ peak with two different mass Gaussians, they rule out a mass difference of less that 3.6 MeV (95% CL) for equal X_H and X_L production [22].

$X(3872) \to D^{*0}\bar{D}^0$

With a data sample containing 447M $B\bar{B}$ meson pairs, Belle observed a near-threshold $D^0\bar{D}^0\pi^0$ mass enhancement in $B \to KD^0\bar{D}^0\pi^0$ decays that, when interpreted as $X(3872) \to D^0\bar{D}^0\pi^0$, gave an $X(3872)$ mass of $3875.4 \pm 0.7^{+1.2}_{2.0}$ MeV [29]. BaBar studied $B \to KD^{*0}\bar{D}^0$ with a sample of 383M $B\bar{B}$ pairs and found a similar near-threshold enhancement that, if considered to be due the the $X(3872) \to D^{*0}\bar{D}^0$, gave a mass of $3875.1^{+0.7}_{0.5} \pm 0.5$ MeV [30]. These mass values are distinctly higher than that seen for the $\pi^+\pi^- J/\psi$ channel and this raised some hope that these may be the neutral partner state predicted by the diquark-diantiquark model. However, a subsequent Belle study of $B \to KD^{*0}\bar{D}^0$ based on 657M $B\bar{B}$ pairs finds a mass for the near threshold peak of $3872.9^{+0.6}_{-0.4}{}^{+0.4}_{-0.5}$ MeV, much closer to the value determined from the $\pi^+\pi^- J/\psi$ decay channel.

In the meantime, Braaten and co-authors have pointed out that in a narrow decaying $D^{*0}\bar{D}^0$ molecular system the decays of the constituent D^{*0} are important and the width of the D^{*0} distorts the decay line shape in this channel [31, 32]. Therefore, fitting the $D\bar{D}\pi$ or $D^*\bar{D}$ to a BW function, as the experiments have done, does not give reliable values for either the mass or width.

Belle study of $B \to K\pi X(3872)$

If, in fact, the $X(3872)$ is a $D^{*0}\bar{D}^0$ molecule, it is a very strange object. The small value for the binding energy given above means that the constituent D^{*0} and $\bar{D}^0$ are generally very far apart in space: for the central value, *i.e.* $E_B = 0.25$ MeV, their rms separation would be a huge 6 fermis or higher [32]. In such a case, the constituent D^* and the $\bar{D}$ would rarely be near enough to each other to allow for the formation of a J/ψ, which has to happen for the $\pi^+\pi^- J/\psi$ decay to occur. Likewise, it would seem that the prompt production of such a fragile object in high energy $p\bar{p}$ collisions, as seen by CDF [14] and D0 [15], would also be improbable. In fact, the production characteristics of the $X(3872)$ in $\sqrt{s} = 1.96$ GeV $p\bar{p}$ collisions, such as the p_T & rapidity distributions and the ratio of prompt production *vs.* production via B-meson decays, are very similar to those of the well established ψ' charmonium state [15, 33].

To get around this, molecule advocates usually conjecture that the physical $X(3872)$ is a quantum mechanical mixture of a $D^*\bar{D}$ molecule and the 2^3P_1 $c\bar{c}$ charmonium state (*i.e.* the χ'_{c1}) and the latter component dominates the production and decays to final states that contain charmonium. Therefore it is of interest to compare production characteristics of the $X(3872)$ to those of other charmonium states in B-meson decays. One common characteristic of all of the known charmonium states that are produced

in B meson decays is that when they are produced in association with a $K\pi$ pair, the $K\pi$ system is always dominated by a strong $K^*(890) \to K\pi$ signal.

Belle did a study of $X(3872)$ production in association with a $K\pi$ in $B^0 \to K^+\pi^-\pi^+\pi^- J/\psi$ decays [21]. In a sample of 657M $B\bar{B}$ pairs they see a signal of about 90 events where the $\pi^+\pi^- J/\psi$ comes from $X(3872)$ decay. Figure 2 shows the $K\pi$ invariant mass distribution for these events, where it is evident that most of the $K\pi$ pairs have a phase space-like distribution, with little or no signal for $K^*(890) \to K\pi$. This should be contrasted to the $B \to K\pi\psi'$ events (with $\psi' \to \pi^+\pi^- J/\psi$) events in the same data sample, where the $K\pi$ invariant mass distribution, shown in Fig. 3, is dominated by the $K^*(890)$.

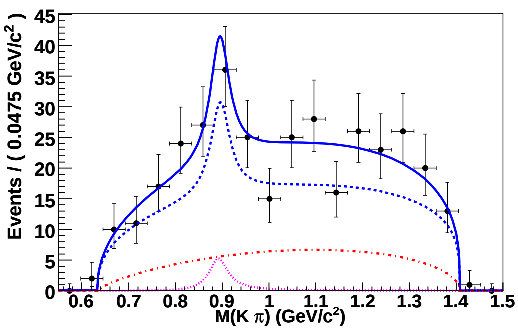

Figure 2: The $K\pi$ mass distribution for $B \to K\pi X(3872)$ events from ref. [21].

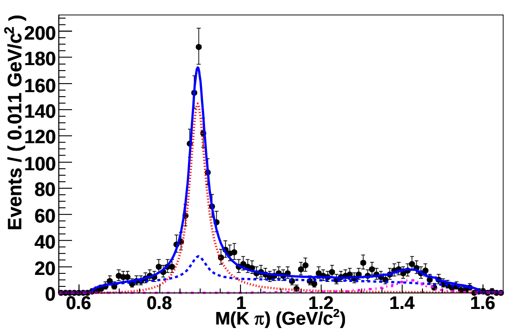

Figure 3: The $K\pi$ mass distribution for $B \to K\pi\psi'$ events from ref. [21].

Belle reports a $K^*(890)$ to $K\pi$ non-resonant ratio of

$$\frac{\mathcal{B}(B \to (K^+\pi^-)_{K^*(890)} J/\psi)}{\mathcal{B}(B \to (K^+\pi^-)_{NR} J/\psi)} < 0.55, \qquad (7)$$

For comparison, from branching fractions listed in the PDG, I estimate the corresponding ratio for $B \to K^+\pi^- J/\psi$ decays to be $\sim$3.0, albeit with a large error.

The 1^{--} states produced by ISR

Thanks to the very high luminosities enjoyed by the B-factory experiments, while they run at the $\Upsilon(4S)$ ($\sqrt{s} = 10.58$ GeV) and nearby continuum, they also accumulate lots of e^+e^- annihilation data at lower energies via the initial-state-radiation process $e^+e^- \to \gamma_{ISR} X$. When the ISR gamma-ray energy is in the $4 \sim 5$ GeV range, the e^+e^- annihilation occurs in the $\sqrt{s'} = 3 \sim 5$ GeV range, the energy region populated by charmonium states. The BaBar group used the ISR process to study the cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ in the charmonium region and discovered a large, relatively broad peak near 4260 MeV [34]. BaBar's fitted mass for this peak, which they call the $Y(4260)$, is $M = 4259 \pm 8^{+2}_{-6}$ MeV and its total width is $\Gamma = 88 \pm 23^{+6}_{-4}$ MeV. The $Y(4260)$ was confirmed by both CLEO [35] and Belle [36]. Belle cross-section measurements for $e^+e^- \to \pi^+\pi^- J/\psi$ in the $\sqrt{s} = 4 \sim 5$ GeV region are shown in Fig. 4, where the cross section at the $Y(4260)$ peak is ~ 70 pb.

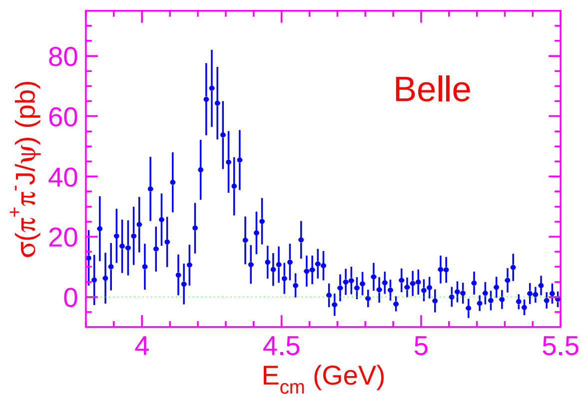

Figure 4: Cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$.

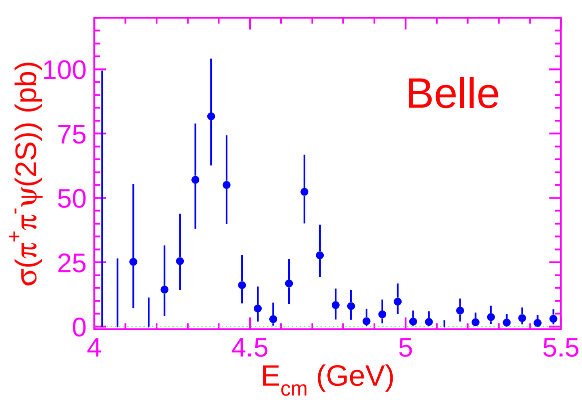

Figure 5: Cross sections for $e^+e^- \to \pi^+\pi^-\psi'$.

The BaBar group subsequently reported a similar structure in the cross section for $e^+e^- \to \pi^+\pi^-\psi'$, but in this case the fitted mass, $M = 4324 \pm 24$ MeV and width $\Gamma = 172 \pm 33$ MeV are both significantly higher than the values found for the $Y(4260)$ [37]. Belle confirmed the general features of the BaBar $\pi^+\pi^-\psi'$ peak but, thanks to a larger data sample (673 fb^{-1} for Belle compared to 272 fb^{-1} for BaBar) they found that the structure is formed from two narrower peaks. Belle's fit to these

two peaks give $M_1 = 4361 \pm 9 \pm 9$ MeV & width $\Gamma_1 = 74 \pm 15 \pm 10$ MeV (the $Y(4360)$) $M_2 = 4664 \pm 11 \pm 5$ MeV & $\Gamma_2 = 48 \pm 15 \pm 3$ MeV (the $Y(4660)$) [38]. Figure 5 shows Belle's $e^+e^- \to \pi^+\pi^-\psi'$ cross section measurements, where the two peak values corresponding to the $Y(4369)$ and the $Y(4660)$ are $\sim$ 80 pb & $\sim$ 50 pb, respectively, and similar to the peak cross-section value for the $Y(4260)$ shown in Fig. 4.

Can these be charmonium states?

There is only one unassigned 1^{--} charmonium state in this mass region, the 3^3D_1 level. This might accommodate the $Y(4660)$, but there is no room in the spectrum for all three of the peaks discussed above. A tantalizing feature of all three of these states is the total absence of any corresponding peaking features in the total cross section for e^+e^- annihilation into hadrons at the same energy. Figure 6 shows BES measurements of $R_{had} = \sigma(e^+e^- \to \mathrm{hadrons})/\sigma_{QED}(e^+e^- \to \mu^+\mu^-)$ in the same energy region, where the cross section exhibits dips near the locations of the $Y(4260)$ and $Y(4360)$ [39]. (The BES R_{had} measurements do not span the $Y(4660)$ region.)

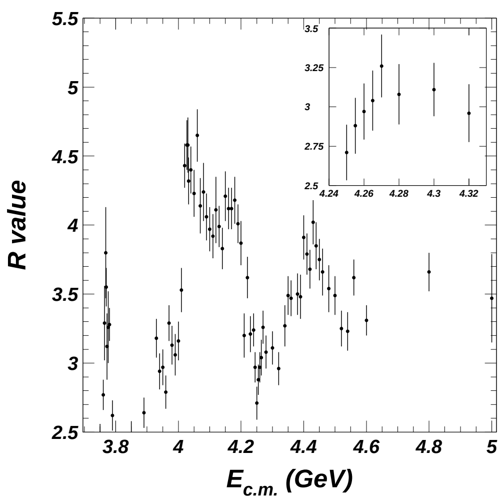

Figure 6: The cross section for $e^+e^- \to$ hadrons in the charmonium region measured by BES (from ref. [40]).

The absence of any evidence for $Y(4260)$ ($Y(4360)$) decays to open charm implies that the $\pi^+\pi^-J/\psi$ ($\pi^+\pi^-\psi'$) partial width is large: the analysis of ref. [40] gives a 90% CL lower limit $\Gamma(Y(4260) \to \pi^+\pi^-J/\psi) > 508$ keV, which should be compared to the corresponding $\pi^+\pi^-J/\psi$ partial widths of established 1^{--} charmonium states: 89.1 keV for the ψ' and 44.6 keV for the ψ'' [23].

Belle and BaBar have exploited ISR to make measurements of cross sections for exclusive open-charm final states in this energy range [41, 42]. These are discussed in detail at this meeting by Galina Pakhlova. She reports that the exclusive channels that have been measured so far — the sum of which very nearly saturates the total inclusive cross section — show no evidence for peaking near the masses of the Y states. The one exception is $e^+e^- \to \Lambda_c^+\Lambda_c^-$, which has a threshold peak in the vicinity of the $Y(4660)$ peak mass [42].

Search for $Y(4260) \to D^{(*)}\bar{D}\pi$ using ISR

The most commonly invoked theoretical explanation for the ISR-produced 1^{--} Y states is that they are $c\bar{c}$-gluon hybrids [43], *i.e.* mesons containing a $c\bar{c}$ pair plus an excited gluonic field. From this point of view, the lack of any evidence for $D^{(*)}\bar{D}^{(*)}$ decays is explained by the theoretically motivated expectation that the relevant open-charm thresholds for $c\bar{c}$-gluon hybrids are $M_{D^{**}} + M_D$, where D^{**} designates the low-lying P-wave charmed mesons: the lowest of these are the very wide $J^P = 0^+$ $D_0(2400)$ with $M \simeq 2350$ MeV and $\Gamma \simeq 260$ MeV, and the narrow $J^P = 1^+$ $D_1(2420)$ with $M \simeq 2420$ MeV and $\Gamma \simeq 20$ MeV. Note that there is considerable overlap between the broad $Y(4260)$ peak and the thresholds for both $D^{**} = D_0(2400)$ and $D^{**} = D_1(2420)$. The prominent decay modes of the $D_0(2400)$ and $D_1(2420)$ are $D\pi$ and $D^*\pi$, respectively. Therefore, searches for the $Y(4260)$ in *both* the exclusive $e^+e^- \to D\bar{D}\pi$ and $D^*\bar{D}\pi$ channels are especially important.

In 2008, Belle [44] published the ISR measurements of $\sigma(e^+e^- \to D^0D^-\pi)$ shown in Fig. 7, show a strong $\psi(4415)$ signal. (This is seen to be due to $\psi(4415) \to D_2^*(2460)\bar{D}$, where $D_2^*(2460)$ is the $J = 2$ D^{**} state, and this observation strongly supports the $\psi(4415)$ assignment to the $\psi(4S)$ charmonium state [8].) However, the data show no indication of a $Y(4260) \to D_0(2400)\bar{D}$ signal as expected for a $c\bar{c}$-gluon hybrid assignment for the $Y(4260)$. In fact, the cross section is consistent with zero throughout the $Y(4260)$ mass region, at least within the $\sim$ ± 100 pb errors of the data points. Note that the cross section (in Fig. 4 above) for $e^+e^- \to \pi^+\pi^-J/\psi$ at the $Y(4260)$ peak is $\sim$ 70 pb, which indicates that $Y(4260) \to D_0(2400)\bar{D}$ decays cannot be much more frequent than $Y(4260) \to \pi^+\pi^-J/\psi$ decays.

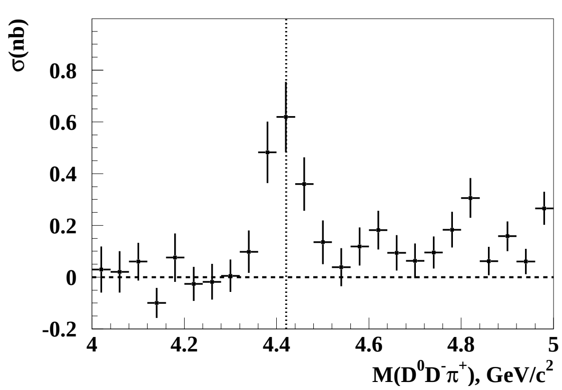

Figure 7: $\sigma(e^+e^- \to D^0D^-\pi^+)$ from ref. [45].

In this meeting, Galina Pakhlova provided the first report of new Belle results for $\sigma(e^+e^- \to D^{*-}\bar{D}^0\pi^+)$ shown in Fig. 8 [45]. Here, although the error bars are larger, there

is also no sign at all of a $Y(4260)$ signal (or, for that matter, a $Y(4350)$ signal, or a $Y(4660)$ signal). The curve in the figure shows a fit that includes a $\psi(4415)$ term and a smooth background; the $\psi(4415)$ signal yield from this fit is $14.4 \pm 6.2^{+1.0}_{-9.5}$ events with a statistical significance of 3.1σ.

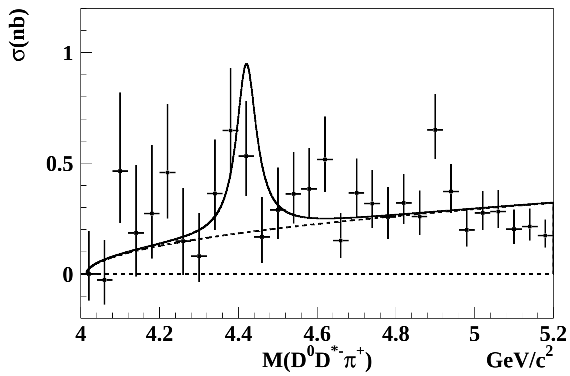

Figure 8: $\sigma(e^+e^- \to D^*\bar{D}\pi)$ distribution from ref. [45]. The curve show results of the fit described in the text.

A fit to the data in Fig. 8 using two incoherent Breit-Wigner functions, one to represent the $Y(4260)$ and the other for the $\psi(4415)$, plus an incoherent smooth background term give a 90% CL upper limit on $\mathcal{B}(Y(4260) \to D^0D^{*-}\pi^+)/\mathcal{B}(Y(4260) \to \pi^+\pi^-J/\psi) < 15$. Consideration of the possibility of coherent destructive interference between the different fit components could inflate this upper limit by as much as a factor of four, but even this would be pretty small compared to ratio between branching fractions for specific open-charm modes and that for $\pi^+\pi^-J/\psi$ for the $\psi(3770)$ charmonium state, which are of the order ~ 250 [23]. Similar limits obtain for the $Y(4350)$ & $Y(4660)$. These results are discussed in Galina Pakhlova's report in these proceedings.

The charged Z states

Belle's $Z(4430)^+$ signal is the sharp peak in the $\pi^+\psi'$ invariant mass distribution from $B \to K\pi^+\psi'$ decays shown in Figure 9 [2]. A fit using a BW resonance function gives a mass of $M = 4433 \pm 4 \pm 2$ MeV and total width of $\Gamma = 45^{+18}_{-13}{}^{+30}_{13}$ MeV, with an estimated statistical significance of more than 6σ. Consistent signals are seen in various subsets of the data: *i.e.* for both the $\psi' \to \ell^+\ell^-$ & $\psi' \to \pi^+\pi^-J/\psi$ subsamples, the $\psi'(J/\psi) \to e^+e^-$ & $\mu^+\mu^-$ subsamples, etc.

Figure 10 shows the Dalitz plot for the $B \to K\pi^+\psi'$ event candidates, where vertical bands for $K^*(890) \to K\pi$ and $K_2^*(1430) \to K\pi$ are evident and the $Z(4430)$ shows up as a horizontal band of events between $M^2(\pi\psi') = 19$ & 20 GeV^2. (In the $M(\pi\psi')$ distribution of Fig. 9, the the K^* bands are suppressed by cuts on the $K\pi$ masses.)

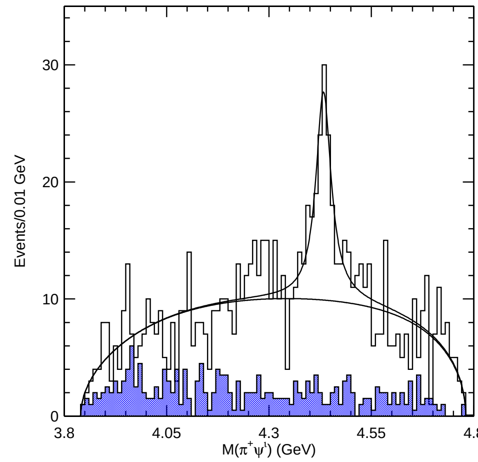

Figure 9: The $\pi^+\psi'$ invariant mass distribution for $B \to K\pi^+\psi'$ decays (from ref. [2]).

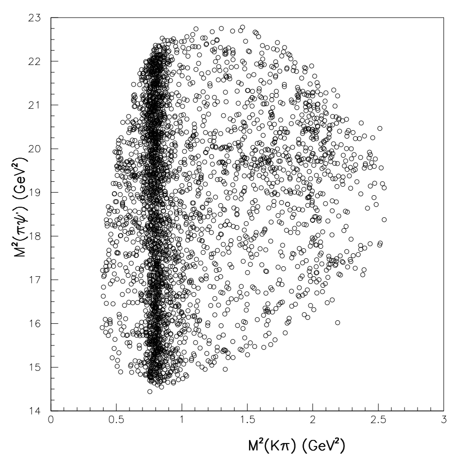

Figure 10: The $M^2(K\pi)$ (horizontal) *vs.* $M^2(\pi\psi')$ (vertical) Dalitz plot distribution for candidate $B \to K\pi\psi'$ events (from ref. [2]).

Is the $Z(4430)^+$ a reflection from $K\pi$ dynamics?

A danger in searching for resonant structures in the $\pi\psi'$ channel in three-body $B \to K\pi\psi'$ decays is the possibility that dynamics in the $K\pi$ channel can cause mass structures in the $\pi\psi'$ invariant mass distribution that have no relation to $\pi\psi'$ dynamics. This is because energy-momentum conservation imposes a tight correlation between the decay angle (θ_π) in the $K\pi$ system [46] and the $\pi\psi'$ invariant mass. In fact, $M^2(\pi\psi')$ is very nearly proportional to $\cos\theta_\pi$. As a result, interference between different partial waves in the $K\pi$ system can produce peaks in the $M(\pi\psi')$ that are merely "reflections" of structures in $\cos\theta_\pi$. However, in the kinematically allowed $K\pi$ mass range for $\to K\pi\psi'$ decay, only S, P and D $K\pi$ partial waves are significant, and this limited set of partial waves can only produce fake $\pi\psi'$ mass peaks at a discrete set of mass values.

In the case of the $Z(4430)$, the $\pi^+\psi'$ peak mass corresponds to $\cos\theta_\pi \simeq 0.25$, and it is not possible to produce a peak near $\cos\theta_\pi \simeq 0.25$ with any combination of interfering $L = 0,\ 1\ \&\ 2$ partial waves without introducing larger additional structures at other $\cos\theta_\pi$ values. This is illustrated in Fig. 11, where the histogram shows the distribution of $\cos\theta_\pi$ values for a MC sample of $B \to KZ(4430)$, $Z(4430) \to \pi\psi'$ events where the Z mass and width closely correspond to Belle's reported values. The curves in the figure show the results of trying to make a peak at at the same location with interfering S, P and D partial waves in the $K\pi$ channel. (Here both longitudinally and transversely polarized ψ''s are considered, and no attempt is made to restrict the strength of each term to that seen for the S-, P- and D-wave $K\pi$ components in the data.) These curves show that although a peak can be made at $\cos\theta_\pi \simeq 0.25$, it is necessarily accompanied by much larger peaks near $\cos\theta_\pi \simeq \pm 1$. No such structures are evident in the $\pi\psi'$ mass plot of Fig. 9.

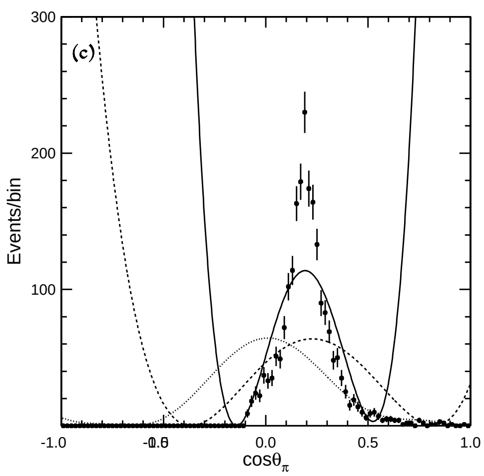

Figure 11: The histogram shows the $\cos\theta_{K\pi}$ distribution for a MC-generated $\pi\psi'$ resonance with $M = 4.43$ GeV and $\Gamma = 0.05$ GeV. The curves show the results of attempts to produce a peak in the vicinity of the data with interfering S, P and D waves in the $K\pi$ channel.

A Dalitz analysis of $B \to K\pi\psi'$

After the BaBar group did not confirm [47] the $Z(4430)^+ \to \pi^+\psi'$ mass peak in their analysis of $B \to K\pi\psi'$ decays [4], the Belle group performed a reanalysis of their data that took detailed account of possible reflections from the $K\pi$ channel. Specifically, they modeled the $B \to K\pi\psi'$ process as the sum of two-body decays $B \to K_i^*\psi'$, where K_i^* denotes all of the known $K^* \to K\pi$ resonances that are kinematically accessible, and both with and without a $B \to KZ$ component, where Z denotes a resonance that decays to $\pi\psi'$ [48]. The results of this analysis, details of which are provided by Ruslan Chistov in these proceedings, confirm the basic conclusions of Belle's 2007 publication.

The data points in Fig. 12 shows the $M^2(\pi\psi')$ Dalitz plot projection with the prominent K^* bands removed (as in Fig. 9) compared with the results of the fit with no Z resonance, shown as a dashed histogram, and that with a Z resonance, shown as the solid histogram. The fit with the Z is favored over the fit with no Z by 6.4σ. The fitted mass, $M = 4443^{+15}_{-12}\ {}^{+19}_{-13}$ MeV, agrees within the systematic errors with the earlier Belle result; the fitted width, $\Gamma = 107^{+86}_{-43}\ {}^{+74}_{-56}$ MeV, is larger, but also within the new analysis'systematic errors of the previous result. In the default fit, the Z resonance was assumed to have zero spin. Variations of the fit the included a $J = 1$ assignment for the Z as well as models that included additional, hypothetical $K^* \to K\pi$ resonances with floating masses and widths, and radically different parameterizations of the $K\pi$ S-wave amplitude do not change the conclusions [49] The product branching fraction from the Dalitz fit: $\mathcal{B}(B^0 \to KZ^+) \times \mathcal{B}(Z^+ \to \pi^+\psi') = (3.2^{+1.8}_{-0.9}\ {}^{+9.6}_{-1.6}) \times 10^{-5}$ is not in strong contradiction with the BaBar 95% CL upper limit of 3.1×10^{-5}.

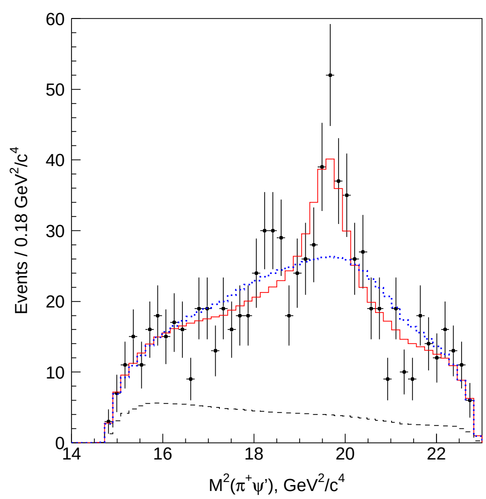

Figure 12: The data points show the $M^2(\pi\psi')$ projection of the Dalitz plot with the K^* bands removed. The histograms show the corresponding projections of the fits with and without a $Z \to \pi\psi'$ resonance term.

Two charged Z peaks in the $\pi^+\chi_{c1}$ channel

In addition to the $Z(4430)^+$, Belle has presented results of an analysis of $B \to K\pi^+\chi_{c1}$ decays that require two resonant states in the $\pi^+\chi_{c1}$ channel [3]. The $M^2(K\pi)$ *vs.* $M^2(\pi\chi_{c1})$ Dalitz plot, shown in Fig. 13, shows vertical bands of events corresponding to $K^*(890) \to K\pi$ and $K_2^*(1430) \to K\pi$, plus a broad horizontal band near $M^2(\pi\chi_{c1}) \simeq 17.5$ GeV^2, indicating a possible resonance in the $\pi^+\chi_{c1}$ channel. In this case, this horizontal band corresponds to $\cos\theta_\pi \simeq 0$, a location where interference between partial waves in the $K\pi$ channel can produce a peak and, thus, a detailed Dalitz analysis is essential.

In this case the kinematically allowed mass range for the

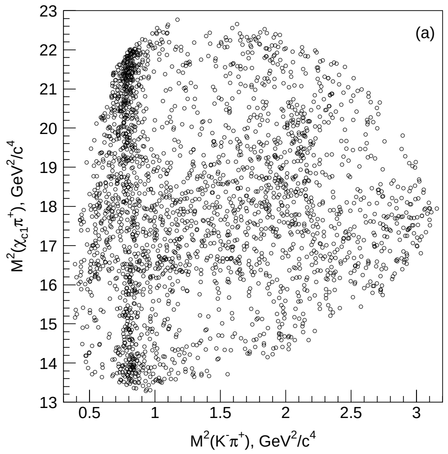

Figure 13: The $M^2(K\pi)$ (horizontal) *vs.* $M^2(\pi\psi')$ (vertical) Dalitz plot distribution for candidate $B \to K\pi\psi'$ events (from ref. [3]).

$K\pi$ system extends beyond the $K_3^*(1780)$ F-wave resonance and S-, P-, D- and F-wave terms for the $K\pi$ system are are included in the model. The fit with a single resonance in the $Z \to \pi\chi_{c1}$ channel is favored over a fit with only K^* resonances and no Z by more than 10σ. Moreover, a fit with two resonances in the $\pi\chi_{c1}$ channel is favored over the fit with only one Z resonance by 5.7σ. The fitted masses and widths of these two resonances are: $M_1 = 4051 \pm 14^{+20}_{-41}$ MeV and $\Gamma_1 = 82^{+21}_{-17}\,^{+47}_{-22}$ MeV and $M_2 = 4248^{+44}_{-29}\,^{+180}_{-35}$ MeV and $\Gamma_2 = 177^{+54}_{-39}\,^{+316}_{-61}$ MeV. The product branching fractions have central values similar to that for the $Z(4430)$ but with large errors. Figure 14 shows the $M(\pi\chi_{c1})$ projection of the Dalitz plot with the K^* bands excluded and the results of the fit with no $Z \to \pi\chi_{c1}$ resonances and with two $Z \to \pi\chi_{c1}$ resonances.

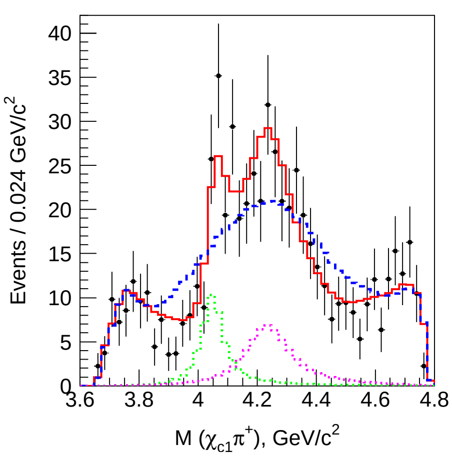

Figure 14: The data points show the $M(\pi\chi_{c1})$ projection of the Dalitz plot with the K^* bands removed. The histograms show the corresponding projections of the fits with and without the two $Z \to \pi\chi_{c1}$ resonance terms.

Summary

The number of XYZ states continues to grow. Here I have reported on a new Belle $X(3915) \to \omega J/\psi$ mass peak in $\gamma\gamma \to \omega J/\psi$ [12]. In another talk at this meeting, Kai Yi reported on the CDF group's evidence for the $Y(4140)$, a narrow $\phi J/\psi$ resonance in $B^+ \to K^+\phi J/\psi$ decays with mass $4143.0 \pm 2.9 \pm 1.2$ MeV and width $11.7^{+8.3}_{-5} \pm 3.6$ MeV [50]. The statistical significance for this state is 3.8σ and it needs to be confirmed in other experiments. However, this may not occur soon since, as Yi pointed out, the B-factory experiments have poor acceptance for $B \to K\phi J/\psi$, with with $\phi J/\psi$ in this mass range.

The mass and width of Belle's new $\omega J/\psi$ peak agrees well with BaBar's mass and width values for the "$Y(3940)$" $\to \omega\pi$ resonance seen in $B \to K\omega J/\psi$ decays. It is likely that these are the same state, and maybe we should start calling the "$Y(3940)$" the $Y(3915)$. The lower mass would make this state more amenable to an assignment as the χ'_{c0} charmonium state, but the large $\Gamma(Y \to \omega J/\psi)$ partial width remains problematic. Belle expects to present an analysis of $B \to K\omega J/\psi$ decays with their full data sample (*i.e.* with nearly four times the data that were used for the original $Y(3940)$ paper) sometime in the near future.

As measurements of the masses of the $X(3872)$ and the D^0 meson improve, the $X(3872)$ gets closer and closer to the $m_{D^0} + m_{D^{*0}}$ mass threshold: $M_{X(3872)} - m_{D^0} - m_{D^{*0}} = -0.35 \pm 0.41$ MeV. Braaten points out that if the J^{PC} of the $X(3872)$ is 1^{++}, as seems most likely, this nearness to the mass threshold implies that the $X(3872)$ has to be an S-wave $D^0\bar{D}^{*0}$ molecular state with a huge, ~ 6 fermi, rms separation. It not clear how the production characteristics in high energy $p\bar{p}$ collisions of such a fragile extended object could be so similar to those of the very compact and tightly bound ψ' charmonium state. Another question is how do the c and $\bar{c}$ quarks in such widely separated open charm mesons ever get close enough to form the J/ψ that is produced in the relatively frequent $\pi^+\pi^- J/\psi$ decay channel?

New data from Belle show no sign for any of the 1^{--} Y states decaying to $D^{**}\bar{D}$ final states, as would be expected if they are $c\bar{c}$-gluon hybrid states. In general, the total lack of any sign of any signals for any of the 1^{--} Y states in the $D^{(*)}\bar{D}^{(*)}$ and $D\bar{D}^{(*)}\pi$ channels suggests that the $\pi^+\pi^- J/\psi$ ($\pi^+\pi^-\psi'$) partial widths might well be much larger than the 508 keV lower limit for the $Y(4260)$ presented in ref. [40]. Any model that addresses these states should include some mechanism to enhance the partial widths for these transition to vector charmonium states. Such a mechanism is not obviously present for 1^{--} $c\bar{c}$-gluon hybrids: for these, Lattice QCD calculations indicate that the $c\bar{c}$ pair is primarily in a spin-singlet state [51]. Thus, rather than being enhanced, transitions to a J/ψ or ψ' are expected to be suppressed because of the required spin-flip of one of the charmed quarks.

If the charged Z states reported by Belle in the $\pi^+\psi'$ and $\pi^+\chi_{c1}$ channels are in fact meson resonances, they would be "smoking guns" for exotics. It is therefore important that the Belle results get confirmed by other experiments. BaBar made an extensive study of $B \to K\pi^+\psi'$ that neither confirmed nor contradicted the Belle $Z(4430)^+$ result. A similar BaBar study of $B \to K\pi^+\chi_{c1}$ might prove more conclusive. CDF can access the $Z(4430)^+$ and we look forward to results from them in the near future. In the meantime, Belle remains confident that their analyses are sound and the peaks that are seen in the $\pi^+\psi'$ and $\pi^+\chi_{c1}$ invariant mass distributions are not due to reflections from dynamics in the $K\pi$ system.

A few final comments

A number of theoretical models have been proposed for the XYZ states:

- molecules, either of two open charmed mesons or of light mesons with charmonium;
- diquark-diantiquarks;
- $c\bar{c}$-gluon hybrids;
- hadroncharmonium, bound states of charmonium with highly excited light mesons.

molecules

Its closeness to the $D^{*0}\bar{D}^0$ mass threshold plus the accumulating evidence for a 1^{++} J^{PC} assignment make the identification of the $X(3872)$ as a loosely bound S-wave $D^{*0}\bar{D}^0$ molecule inescapable [52]. Although some of the other states are near two-body thresholds (*e.g.* the $Y(4660)$ is near the $f_0(980)\psi'$ threshold and has been attributed to an $f_0(980)\psi'$ molecule [53]), this is not a universal feature of these states. One difficulty with interpreting a state as bound light meson plus charmonium system is the identification of a binding mechanism. The π, ρ, ω, etc. mesons do not couple to charmonium states and, thus, normal nuclear-physics-like binding mechanisms do not apply.

In a talk presented at this meeting, Raquel Molina presented an interesting model that identified the $Y(3940$, $Z(3940)$ & $X(4160)$ as dynamically generated states produced by $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ interactions [54]. This model reproduces the measured masses of these states quite well, but does not address other properties, like the large $\omega J/\psi$ partial width of the $Y(3940)$. In his talk, Daniel Gamermann presented a dynamical model that forms the $X(3872)$ from $D^*\bar{D}$ interactions and explicitly addresses the decays of the $X(3872)$ to $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\pi^0J/\psi$ [55].

diquark-diantiquarks

The diquark-diantiquark picture necessarily implies the existence of a rich array of Isospin and Flavor-$SU(3)$ partners for each of the XYZ states. To date, no such partner states have been observed.

$c\bar{c}$-gluon hybrids

Problems with $c\bar{c}$-gluon hybrid assignments are discussed above. Although these continue to be the favored interpretation for the 1^{--} Y states, this is not because of any of their specific properties (other than their masses) that have been measured to date. $c\bar{c}$-gluon hybrids are necessarily electrically neutral, so this interpretation does not apply to the charged Z states.

Hadrocharmonium

Dubynskiy and Voloshin have investigated a QCD version of a van der Waal's force and found that it can be sufficiently strong to bind light hadrons to a charmonium core in the case where the light hadron is a highly excited resonance [56]. The resulting "hadro-charmonium" states would rather naturally have large partial widths for decays to light hadrons plus charmonium, which is a common feature of the XYZ states. However, this idea has not been used to make any detailed predictions, so it is difficult to evaluate its applicability. Note that this scheme probably cannot be invoked to bind an $f_0(980)$ to a ψ' to form a $Y(4660)$ according to the suggestion of ref. [53] mentioned above, since the $f_0(980)$, a ground-state scalar meson, is hardly a highly excited resonance.

The XYZ states remain a mystery and, therefore, continue to be interesting.

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References

[1] The inclusion of charge-conjugate modes is always implied. Also, when two errors are presented, the first one is always statistical and the second systematic.

[2] S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 142001 (2008).

[3] R. Mizuk *et al.* (Belle Collaboration), *Phys. Rev. D* **78**, 072004 (2008).

[4] B. Aubert *et al.* (BaBar Collaboration), arXiv:0811.0564, submitted to *Phys. Rev. D.*

[5] K. Abe *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **98**, 082001 (2007).

[6] S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **94**, 182002 (2005).

[7] S. Uehara *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **96** 082003, (2006).

[8] T. Barnes, S. Godfrey and E.S. Swanson, *Phys. Rev. D* **72** 054026, (2005).

[9] P. Pakhlov *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 202001 (2008).

[10] N. Zwahlen *et al.* (Belle Collaboration), arXiv:0810.0358.

[11] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **101**, 082001 (2008).

[12] S. Uehara *et al.* (Belle Collaboration), in preparation.

[13] S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **91**, 262001 (2003).

[14] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **93**, 072001 (2004).

[15] V.M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **93**, i62002 (2004).

[16] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **71**, 071103 (2005).

[17] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **96**, 102001 (2006).

[18] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **98**, 132002 (2007).

[19] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **102**, 132001 (2009).

[20] See, for example: F.E. Close and P.R. Page, *Phys. Lett.* **B578**, 316 (2004), M.B. Voloshin, *Phys. Lett.* **B579**, 316 (2004), S. Pakvasa and M. Suzuki, *Phys. Lett.* **B579**, 67 (2004), E.S. Swanson, *Phys. Lett.* **B588**, 189 (2004), N. Tornqvist, *Phys. Lett.* **B590**, 209 (2004) and E. Braaten, M. Kusunoki and S. Nussinov, *Phys. Rev. Lett.* **93**, 162001 (2004).

[21] I. Adachi *et al.* (Belle Collaboration), arXiv:0809.1224.

[22] A. Abulencia *et al.* (CDF Collaboration), arXiv:0906.5218.

[23] C. Amsler *et al.* (Particle Data Group) *Phys. Lett.* **B667**, 1 (2008).

[24] L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, *Phys. Rev. D* **71**, 014028 (2005).

[25] D. Ebert, R.N. Faustov and V.O. Galkin *Phys. Lett.* **B634**, 1 (2006).

[26] This is $2(m_d - m_u)/\cos 2\theta$, where m_d (m_u) is the d-quark (u-quark) mass and $\theta \simeq 20^0$ is a mixing angle.

[27] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **71**, 031501 (2005).

[28] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **77**, 111101 (2008).

[29] G. Gokhroo *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **97**, 162002 (2006).

[30] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **77**, 011102 (2008).

[31] E. Braaten and M. Lu, *Phys. Rev. D* **76**, 094028 (2007).

[32] E. Braaten and J. Stapleton, arXiv:0907.3167

[33] G. Bauer, *Int. J. Mod. Phys.* **A20**, 3767 (2005).

[34] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **95**, 142001 (2005).

[35] T. Coan *et al.* (CLEO Collaboration), *Phys. Rev. Lett.* **96**, 162003 (2006).

[36] C.-Z. Yuan et al. (Belle Collaboration), *Phys. Rev. Lett.* **99**, 182004 (2007).

[37] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **98**, 212001 (2007).

[38] X.-L. Wang et al. (Belle Collaboration), *Phys. Rev. Lett.* **99**, 142002 (2007).

[39] J.Z. Bai *et al.* (BES Collaboration), *Phys. Rev. Lett.* **88**, 101802 (2002).

[40] X.-L. Wang *et al.*, *Phys. Lett.* **B640**, 182 (2007).

[41] G. Pakhlova *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **98**, 062001 (2007). *Phys. Rev. D* **77**, 011103 (2007).

[42] G. Pakhlova *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **101**, 172001 (2008).

[43] See, for example: F.E. Close and F.E. Page, *Phys. Lett.* **B628**, 215 (2005) and E. Kou and O. Pene, *Phys. Lett.* **B631**, 164 (2005).

[44] G. Pakhlova *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 062001 (2008).

[45] G. Pakhlova *et al.* (Belle Collaboration), arXiv: 0908.0231.

[46] θ_π is the angle between the π^+ and the negative of the ψ' direction in the $K\pi$ rest frame.

[47] BaBar reports a 1.9σ signal with mass and width similar to Belle's; if the mass and width are fixed at the Belle values, the significance increases to 3.1σ.

[48] R. Mizuk *et al.* (Belle Collaboration), *Phys. Rev. D* **80**, 031104 (2009).

[49] Variations in fit values from these alternative models are the main sources of the large systematic errors.

[50] A. Aaltonen *et al.* (CDF Collaboration), arXv:0903.2229.

[51] See, for example, J.J. Dudek and E. Rrapaj, *Phys. Rev. D* **78**, 094504 (2008).

[52] Eric Braaten, private communication.

[53] F.-K. Guo, C. Hanhart and U.-G. Meissner *Phys. Lett.* **B665**, 26 (2008).

[54] R. Molina and E. Oset, arXiv:0906.5333

[55] D. Gamermann and E. Oset, *Phys. Rev. D* **80**, 14003 (2009).

[56] S. Dubynsky and M.B. Voloshin, *Phys. Lett.* **B666**, 344 (2008).